EDWARD TELLER SCIENCE & TECHNOLOGY SYMPOSIUM

Lawrence Livermore National Laboratory

PHYSICS SECTION

Introduction:

Introductory Physics textbooks and courses typically include one or more units of study in light & optics. The California State Content Standards for Grades 9-12 include the following standard:

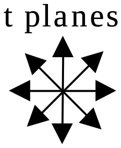
> 4. Waves have characteristic properties that do not depend on the type of wave. As a basis for understanding this concept, students know:
>
>   f. How to identify the characteristic properties of waves: interference (beats), diffraction, refraction, Doppler effect, and polarization.

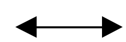
In these lessons, teachers will learn extensions, applications, and classroom activities related to the concept of polarization.

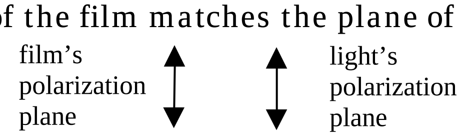
Background:

Polarization:

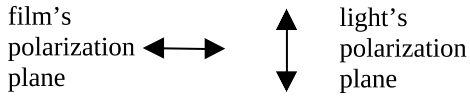
A single transverse light wave oscillates in a plane as it travels – viewed traveling into or out of the page, its electric field might oscillate like this: 

Ordinary light emitted from an incandescent light bulb or the sun consists of a mixture of transverse light waves that, in addition to having a variety of wavelengths and phases, oscillate in many different planes – viewed traveling into or out of the page, their electric fields might vibrate like this: 

When light is polarized, the waves are confined to a single plane of oscillation. 
As noted above, light from typical sources such as room lights or the sun is not polarized when it is emitted. One common way light becomes polarized occurs when the light passes through a material that only transmits one plane of polarization. Natural materials that have this effect include quartz and calcite. Man-made materials that can polarize light include Polaroid films, liquid crystals, and stretched plastics.

Polaroid films can be used to detect and analyze polarized light. When polarized light is viewed through a Polaroid film, as the film is rotated the light will vary in brightness, and the light will go from brightest to darkest with a 90° rotation of the Polaroid film. When the light is brightest, the plane of polarization of the film matches the plane of polarization of the light, allowing maximum transmission: 

As the film is rotated, the film only transmits the component of the light's electric field vector that is aligned with the film's plane of polarization. This alignment decreases as the film rotates, until the plane of polarization of the film is perpendicular to the plane of polarization of the light, and no light is transmitted:



Unpolarized light viewed through a Polaroid film maintains a uniform brightness as the film is rotated.

<u>Refractive Index (or Index of Refraction):</u>

The speed of light in a vacuum is 2.9979_10^{8} m/s. Light travels slower in materials than in a vacuum. The refractive index, *n*, is a measure that compares the speed of light in a material to the speed of light in a vacuum:

$$n = \frac{c}{v}$$

Here *c* is the speed of light in a vacuum, and *v* is the speed of light in the material. Since light's speed is a maximum in a vacuum, *n* will never be less than 1, and the larger the value of *n*, the slower the light speed in that material. For example, the refractive index for air is 1.0003, water is 1.33, and diamond is 2.42.

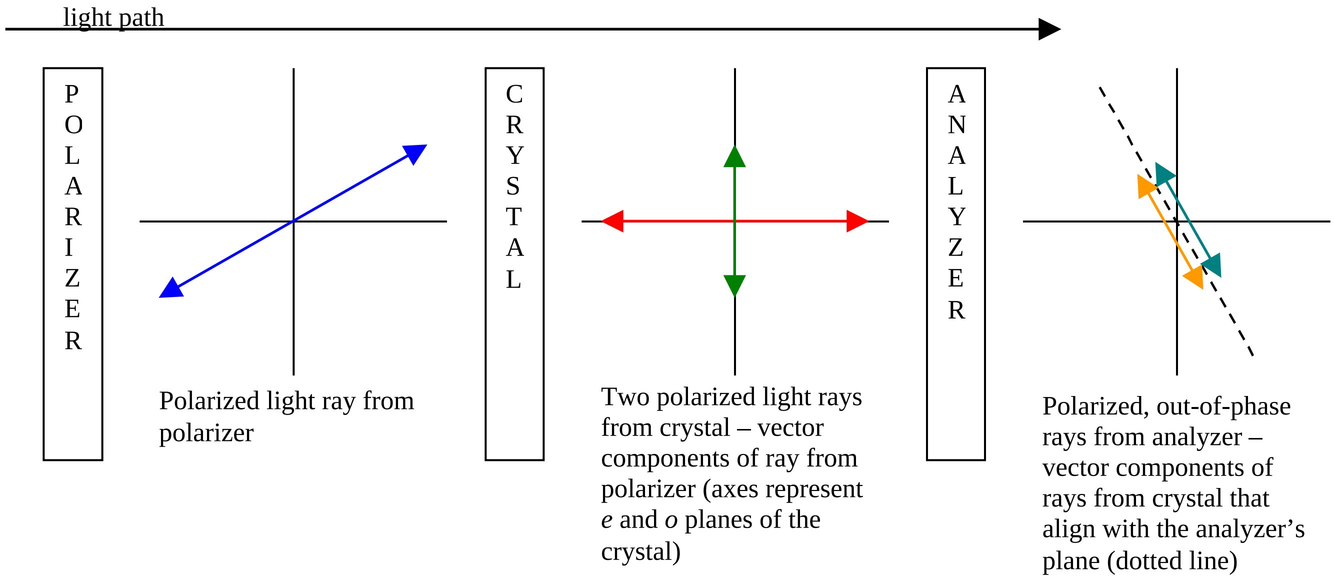
<u>**Research and Practical Applications Related to Polarization:**</u>

<u>Birefringence:</u>

In *isotropic* materials such as glass, the refractive index is the same no matter which direction light passes through the material. Other transparent materials such as quartz are *anisotropic*, meaning they have different refractive indices in different directions. An anisotropic material that has two different refractive indices is said to be *birefringent*.

When a ray of unpolarized light passes through a birefringent crystal along its optic axis, the ray encounters only one refractive index and leaves the crystal unchanged. But when a ray of unpolarized light enters the birefringent crystal at an angle to its optic axis, the beam is split into two polarized rays – the ordinary (*o*) ray, which travels through the crystal without any refraction, and the extraordinary (*e*) ray, which is refracted following Snell's Law. These two rays are thus offset from each other both in phase and in space, and have planes of polarization that are mutually perpendicular. Objects viewed through the birefringent crystal thus produce a double image.

Passing polarized light through a crystal allows discovery of its properties. Typically the material is placed between two crossed Polaroid films (their planes of polarization are mutually perpendicular). Light is shined through the first film, the polarizer, then through the crystal, then through the second film, the analyzer. If the crystal has no effect on the polarized light, the crystal will appear dark, since the analyzer blocks out the plane of polarization coming from the polarizer. Hold a birefringent crystal between the polarizers so that the crystal appears dark, and you have located the plane of polarization of the *e* or *o* ray (it will have the same orientation as the polarizer). Rotate the crystal to another dark position 90 degrees from the first, and you have located the plane of polarization of the other ray. Hold the crystal at an orientation somewhere between the two ray directions, and it appears bright. In this case, the polarized light from the polarizer is split into two vector components by the crystal – these components are aligned with the *e* and *o* ray directions.



When these two rays from the crystal encounter the analyzer, the vector component of each ray that aligns with the polarizer is transmitted, and the other component is not. Two rays emerge, both dimmer than the original ray, and one is phase shifted relative to the other. These rays make the crystal appear bright, while the surrounding light going straight from polarizer to analyzer is dark.

There is an additional effect of birefringence. The *e* and *o* rays travel at different speeds through the crystal due to their different refractive indices. So while they were in phase upon entering the crystal, one ray exits the crystal slightly behind the other ray, resulting in a phase shift for one ray relative to the other. The magnitude of the phase shift depends on the thickness of the crystal.

If the two rays exit the crystal in phase, their vector sum leads to one wave, linearly polarized at 45 degrees. This is shown in the diagram at right.

Similarly, if the two rays are 180 degrees out of phase, the resultant is linearly polarized at 45 degrees in the opposite sense.

If the two waves are 90 degrees out of phase, the resulting wave is circularly polarized. In effect, the resultant electric field vector from the sum of the components rotates around the origin as the wave propagates.

The most general case is when the phase difference is at an arbitrary angle (not necessarily 90 or 180 degrees.) This is called elliptical polarization because the electric field vector traces out an ellipse (instead of a line or circle as before.)

For further information, see the web site on Birefringence in Liquid Crystals from Case Western Reserve University at: http://plc.cwru.edu/tutorial/enhanced/files/lc/biref/biref.htm.

Classroom Activity: Polariscope

Materials:
1 section of PVC pipe, hacksaw, two polarizing films, microscope slide, cellophane tape, flashlight, mica sheet

What to Do:
Construct the Polariscope. Shine the flashlight into one end of the polariscope, and view the light from the other end. Hold an object in the polariscope window. Rotate the object around and observe. Does the brightness of the light passing through the object depend on its orientation? Does the object polarize light? If so, is it birefringent? Determine its plane(s) of polarization. Repeat for a variety of objects.

Notes:

Liquid Crystal Displays:

Note: This section on Liquid Crystal Displays is taken from the Case Western Reserve University PLC Project Virtual Textbook web site at: http://plc.cwru.edu/tutorial/enhanced/files/lcd/intro.htm.

The most common application of liquid crystal technology is in liquid crystal displays (LCDs). From the ubiquitous wristwatch and pocket calculator to an advanced VGA computer screen, this type of display has evolved into an important and versatile interface.

A liquid crystal display consists of an array of tiny segments (called pixels) that can be manipulated to present information. This basic idea is common to all displays, ranging from simple calculators to a full color LCD television.

Why are liquid crystal displays important? The first factor is size. An LCD consists primarily of two glass plates with some liquid crystal material between them. There is no bulky picture tube. This makes LCDs practical for applications where size (as well as weight) is important. In general, LCDs use much less power than their cathode-ray tube (CRT) counterparts. Many LCDs are reflective, meaning that they use only ambient light to illuminate the display. Even displays that do require an external light source (i.e. computer displays) consume much less power than CRT devices.

Liquid crystal displays do have drawbacks. Problems with viewing angle, contrast ratio, and response time still need to be solved before the LCD replaces the cathode-ray tube. However with the rate of technological innovation, this day may not be too far into the future.

There are many types of liquid crystal displays, each with unique properties. The most common LCD that is used for everyday items like watches and calculators is called the *twisted nematic* (TN) display. This device consists of a liquid crystal sandwiched between two plates of glass. A special surface treatment is given to the glass so the molecules are homeotropic (the molecules are aligned normal to the boundary surfaces) yet the director (the molecular direction of preferred orientation in the liquid crystal) at the top of the sample is perpendicular to the director at the bottom. This configuration sets up a 90-degree twist into the bulk of the liquid crystal, hence the name of the display. The twist is visible in the graphic at right.

The underlying principle in a TN display is the manipulation of polarized light. When light enters the TN cell, the polarization state twists with the director of the liquid crystal material. For example, consider light polarized parallel to the director at the top of the sample. As is travels through the cell, its polarization rotates with the molecules. When the light emerges, its polarization has rotated 90 degrees from when it entered.

A schematic of a TN cell is shown in the following graphics. The black lines represent crossed polarizers that are attached to the top and bottom of the display. As light enters the cell, its polarization rotates with the molecules. When the light reaches the bottom of the cell, its polarization vector has rotated by 90 degrees, and now can pass through the second polarizer. In a reflecting TN display, a mirror is placed at the bottom of the cell to reflect the transmitted light. Once again the polarization twists as the light traverses the sample, and is able to emerge from the top of the cell. The following graphics show how light entering the cell twists along the way. Light emerging from such a cell appears the familiar silver-gray color.

When an electric field of sufficient magnitude is applied to a sample, the molecules are reoriented, as shown in the graphic at right. Note that in this state, the twist is destroyed. The director of the bulk liquid crystal is parallel to the field and no longer twisted.

When polarized light enters a cell in such a configuration, it is not twisted, and is canceled by the second polarizer. Regions where an electric field is applied appear dark against a bright background.

Now let's step through the various components of a liquid crystal display and briefly mention their functions. A liquid crystal display is composed of multiple layers. First, a sheet of glass is coated with a transparent metal oxide film (shown as a blue layer in the graphic at right), which acts as an electrode. This film can be patterned to form the rows and columns of a passive matrix display or the individual pixels of an active matrix display. These electrodes are used to set up the voltage across the cell necessary for the orientation transition. Next, a polymer alignment layer is applied (shown in red). This layer undergoes a rubbing process, which leaves a series of parallel microscopic grooves in the film. These grooves help align the liquid crystal molecules in a preferred direction, with their longitudinal axes parallel to the grooves. This anchors the molecules along the alignment layers and helps force the molecules between the alignment layers to twist. Two such sheets of glass are prepared and one is coated with a layer of polymer spacer beads (the slightly green glassy layer). These beads maintain a uniform gap between the sheets of glass where the liquid crystals are eventually placed. The two glass sheets are then placed together and the edges are sealed with epoxy. A corner is left unsealed so that the liquid crystal material can be injected under a vacuum. Once the display has been filled with liquid crystals, the corner is sealed and polarizers (the transparent layers with lines) are applied to the exposed glass surfaces. In a TN display (which is shown) the alignment layers are positioned with their rubbing directions perpendicular to each other and the polarizers are applied to match the orientation of the alignment layers. In an STN (super-twisted nematic) display the alignment layers are placed with their rubbing directions at a variety of angles to one another to set up a twist from 180 to 270 degrees and the polarizers are not applied parallel to the alignment layers. The display is finished off by completing the connections to the driving circuitry, which controls the voltage applied to various areas of the display (pixels).

Depending on the field strength, twisted nematic displays can switch between light and dark states, or somewhere in between (grayscale.) How the molecules respond to a voltage is the important characteristic of this type of display. The response of a typical twisted nematic cell to an applied voltage is shown in the diagram at right (called an electro-distortional curve). The tilt of the molecules out of the plane of the glass slides is measured as a function of the applied voltage.

In the TN display, the electro-distortional response determines the transmission of light through the cell. Percent transmission as a function of voltage is shown in the diagram at right. Keep in mind that maximum transmission for a reflective TN device is only 50 percent because polarized light must be used. The vertical lines represent the voltages at which the cell is OFF or ON.

The difference between the ON and OFF voltages in displays with many rows and columns can be very small. For this reason, the TN device is impractical for large information displays. This problem was solved in the mid 1980's with the invention of the super-twisted nematic (STN) display. In this device, the director rotates through an angle of 270 degrees, compared with the 90 degrees for the TN cell. The effect of twist angle on the electro-optical response curve is shown in the diagram at right. Note that the change in the tilt angle becomes very abrupt as the twist angle is increased. The consequence of this response curve is that the off and on voltages are much closer together, as is shown in the figure below right. Although it is desirable to obtain a sharp electro-optic transition, grayscale images require intermediate points along the curve. For this reason, many commercial STN displays use a twist angle of 210 degrees. This broadens the transition region enough for grayscale.

Display Addressing is the process by which pixels are turned on and off in order to create an image. There are two main types of addressing, direct and multiplexing. Direct addressing is convenient for displays where there are only a few elements that have to be activated. With direct addressing, each pixel in the display has its own drive circuit. A microprocessor must individually apply a voltage to each element. A common application of direct addressing is the traditional seven-segment liquid crystal display, found in wristwatches and similar devices. In multiplex addressing, a larger number of pixels are involved. When the elements are in a regular order, they can be addressed by their row and column instead of each element being driven separately. This reduces the complexity of the circuitry because each pixel no longer needs its own driver circuit. If you have a 10x10 matrix of pixels, with direct addressing, you need 100 individual drivers. However, if you use multiplex addressing, you only need 20 drivers, one for each row and one for each column. This is a tremendous advantage, especially as displays become larger and larger.

For more information about related topics such as Passive & Active Matrix Displays, and Color Displays, please see the PLC web site at:
http://plc.cwru.edu/tutorial/enhanced/files/lcd/address/address.htm

Classroom Activity: Analyzing a Commercial LCD

Materials:
9 digit LCD display, wire, battery, polarizer

What To Do:
Systematically connect the LCD display wires across two connectors of the pins. Observe what happens. Map out the pin combinations and display segments. With some of the segments still active (dark), observe the LCD through the polarizer. Rotate the polarizer. What happens and why?

Notes:

Classroom Activity: Making Your Own LCD

Materials:
Two microscope slides covered with thin conductive layer (Gold or indium tin oxide) connected to copper tape, two wires, parafilm, E7 liquid crystal display medium, X-acto knife, capillary tube, LCD shutter assembly

What To Do:
First insert the glass slides and parafilm in the polariscope. Note the absence of birefringence in these construction materials. Carefully using the knife cut a small square in the center of the parafilm. Place the parafilm on the center of one of the gold slides. Using the capillary tube add one drop of E7 to the center of the parafilm hole. Sandwich the second slide over the first to make a cross. Attach the electrodes and carefully put the LCD in the polariscope. Note that birefringence is now observed.

Notes:

LLNL Application: Plasma Electrode Pockels Cell for NIF

The NIF (National Ignition Facility) Plasma Electrode Pockels Cell (PEPC), the world's largest Pockels cell, provides voltage control of the laser beam polarization within the main laser amplifier cavity. Used in conjunction with a thin film polarizer, the PEPC acts as an optical switch. When the switch is "ON," the amplifier cavity is closed, and the optical pulse is trapped in the cavity for multipass amplification. When the switch is "OFF," the cavity is open, and the optical pulse can be injected or switched out of the cavity.

A Pockels cell is part of an Optical Switch that enables a cost-effective, multipass amplifier. In any Pockels cell, an electric field is applied to an electro-optic crystal. This induces birefringence in the crystal, which changes the polarization state of a light wave propagating through the crystal. If the proper voltage is applied to the crystal, the polarization of an incoming, linearly polarized laser beam is rotated exactly 90 degrees. Thus, an optical switch can be realized by placing a polarizer next to a Pockels cell.

If a normal-incidence, absorptive polarizer is used, the laser beam either passes through the polarizer or not depending on whether or not voltage is applied to the Pockels cell. This configuration is often called a Q-switch or gain switch and is used in many pulsed lasers. If an absorptive-reflective polarizer oriented at an angle to the beam is used, the laser beam either passes through or reflects from the polarizer depending on whether or not voltage is applied to the Pockels cell. This is the configuration used on NIF and in other regenerative, multi-pass laser amplifiers.

Figure 1. This figure shows how the PEPC and a polarizer control the multi-pass operation of the NIF amplifier. LM= Laser Mirror, MA= Main Amplifier, CSF= Cavity Spatial Filter, PC= Pockels Cell, P= Polarizer

Figure 1 above shows diagrams of the cavity portion of the NIF laser for each of the four passes the optical pulse makes through the PEPC. First, a shaped optical pulse 20 nanoseconds in duration is injected at the mid-plane of the transport spatial filter and travels backward (away from the target chamber). The pulse enters the amplifier cavity by reflecting from the polarizer (Pass 1). It then propagates through the PEPC, which is initially off so the beam polarization is not changed. The polarization at this point is horizontal which is the proper polarization to pass through the amplifier. About 10 nanoseconds after the pulse passes through the PEPC, we start to apply voltage to the PEPC in the form of a 17,000-volt pulse. Light travels about one foot every nanosecond. It takes about 100 nanoseconds to fully apply this pulse to the PEPC. In the mean time, the optical pulse has passed through the cavity amplifier, reflected from the mirror at the far end of the cavity and passed through the amplifier a second time. After about 275 nanoseconds, the optical pulse returns to the PEPC, which is now fully on (Pass 2). The polarization is rotated 90 degrees (to vertical polarization) so it passes through the polarizer. The pulse then reflects from a mirror at this end of the cavity and back through the PEPC (Pass 3) where the polarization is rotated another 90 degrees (back to horizontal). The pulse then returns to the amplifier end of the cavity for two more gain passes. In the mean time, the PEPC voltage pulse ends and the voltage across the crystal decays to zero. By the time the optical pulse returns to the PEPC again, the PEPC is off so the polarization of the optical pulse is not rotated and it reflects from the polarizer, out of the cavity and back towards the target chamber (Pass 4).

For more information, see the LLNL NIF web site at: http://lasers.llnl.gov/lasers/nif/PEPC/.

Career Connections:

UC Davis' Department of Applied Science offers a Bachelor of Science Program in Optical Science and Engineering. The department has facilities in both Davis and Livermore, and many members of its faculty also work at LLNL. The department also offers an M.S. degree, and PhD degrees in a variety of physics-related subjects. For more information, see their web site at: http://www.engr.ucdavis.edu/~das/ (Select the "Admissions" button, to access information about their undergraduate and graduate programs).

Las Positas College has an Engineering Transfer Program, with a Transfer Option in Optical Science and Engineering, allowing students to transfer to the UCD Department of Applied Science. For more information, see their web site at: http://www.clpccd.cc.ca.us/lpc/eng.shtml.